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Trend analysis of Climatic Research Unit temperature dataset for Gangotri glacier, India

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ABSTRACT

The absence of continuous long term meteorological dataset has led to limited knowledge of glaciers' response to climate change over Himalayas. This study presents an open source long term temperature dataset Climatic Research Unit (CRU) available since 1901 to study trend analysis of temperature (T_{max}, T_{min} and T_{mean}) for Gangotri basin in Himalayas. The study first establishes close agreement between CRU time series data and observed temperature dataset available from National Institute of Hydrology (NIH), Roorkee for a period of 11 years from 2005 to 2015 using standard anomaly, Wilcoxon Signed-Rank (WSR) and correlation tests. The close agreement of CRU with NIH data validate the use of CRU time series to study variation in meteorological parameter for hilly terrain of Himalayas. The second part includes application of different statistical tests such as Mann-Kendall (MK), Sen's slope and CUSUM technique on CRU data to detect existence of any possible trends and identification of change points in T_{max}, T_{min} and T_{mean} on long term scale. On annual scale, significant increasing trends for T_{mean} and T_{min} were observed with no significant trend for T_{max}. On seasonal and monthly scale, T_{max} showed significant decreasing trend for monsoon season and increasing trend for winters while T_{min} show significant increasing trend for all months (except May) and seasons. CUSUM technique identified 8 change points from 3 annual time series with 2 for T_{mean} (1974 and 1999), 3 each for T_{max} (1941, 1975 and 1999) and T_{min} (1941, 1965 and 1999) respectively. Overall, significant increase in T_{min} with no significant trend for T_{max} has been identified over the study area.

1. Introduction

Climate is an essential factor for sustainable development of any country such as India. Temperature and Rainfall are two of the most important climate variables to report climate change. It is highly likely that any change in temperature and precipitation of this region will change the melt characteristics of the Himalayan glaciers (Immerzeel et al., 2010). Any change in glacial activity is going to affect fresh water supply and food security of the region. Various research works (Piyoosh and Ghosh, 2016; Koppes et al., 2015; Rao et al., 2014; Robertson et al., 2013; Rai et al., 2012) has established a close agreement between CRU and India Meteorological Department (IMD) datasets and have even preferred CRU over IMD data to study climate change impact on Indian conditions due to its finer resolution of 0.5°.

Piyoosh and Ghosh (2016) had reported resemblance in pattern of annual standardized anomalies of T_{max} and T_{min} for CRU and IMD datasets for Dehradun city in India obtaining same results from both datasets. Rao et al., (2014) has done analysis of CRU dataset with a focus on influence of temperature on agricultural production (Rabi and Kharif crops) in India at a very fine scale of district

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level from 1971-2009. The rise of 0.24 °C/10 years has been reported in annual mean minimum temperature with an increase of 0.28 °C/10 years and 0.19 °C/10 years in seasonal mean temperatures for rabi and kharif crops.

Robertson et al., (2013) compared interannual variability of maximum, minimum and mean time series temperature data obtained from CRU and IMD sources from 1982 to 2005 for a specific grid box (26.5 N, 80.5E) located in Northern India. The results reported a good amount of correlation between both datasets for mean and minimum time series over the winter season. Rai et al., (2012) examined variation of surface air temperature trends and effect of global warming on global T_{mean} over India at seasonal and annual scale by using temperature anomalies from CRU from 1961 to 1990. The close agreement of CRU with IMD dataset, providing the advantage of finer resolution and open source policy, has resulted in giving preference to CRU over IMD dataset.

The studies (Koppes et al., 2015; Rupper et al., 2012) have utilized CRU dataset to study change in climatic patterns in Himalayan glaciers. Koppes et al., (2015) has used CRU and seven other climate datasets to study distribution of mean surface temperature and its effect on glacial melt water runoff estimates in upper Indus river watershed. The result reveals that mean annual glacier melt contribution to total annual runoff varies from 8 to 169 km^3/yr or from 4% to 78%. The spatial pattern in glacial melt was highly correlated across all datasets despite differences between climate datasets. Rupper et al., (2012) studied sensitivity and response of glaciers of Bhutan to atmospheric warming. The results indicate that 10% of glacierised area in Bhutan would vanish with 30% drop in melt water flux, if there were no significant change in normal mean values. With an increase in mean temperature by 1%, retreat in glaciers of Bhutan would continue and decrease by 25% and annual melt water flux would decrease by 65%.

This work presents possible use of open source climate dataset to study climatic variations for higher glacierised regions of Uttarakhand. Due to difficulties in field measurements of remote hilly areas and a non-continuous limited meteorological data, open source CRU data provides a good alternative to study any change in climatic profiles of these regions. The close agreement between CRU and IMD datasets has already been established the usefulness of CRU data to study climatic variations in different parts of India where spatial variability is low. However, due to greater spatial variability in mountainous regions of India usefulness of CRU data remains to be established. This study focuses on use of CRU data for hilly regions after comparing it with observed temperature dataset for a period of 11 years and this observed data is available through NIH Roorkee under Snow and Glacier laboratory. Hence, this study contains a comparative assessment of T_{max}, T_{min} and T_{mean} of CRU and NIH dataset on a monthly scale. Later, change points and climatic trends were identified using CUSUM technique, Mann-Kendall and Sen's slope tests on CRU dataset.

2. Study area

Gangotri glacier is located in Central Himalayas, originating from Chaukhamba peaks which is at 7138 m above sea level. The glacier is source of river Ganga which is of high religious culture in India. It is around 30 km long with 2.5 Km width flowing in North-West direction (Singh et al., 2017). The location of study area has been shown in Fig. 1. Gangotri glacier lies within 30°43'N - 31°01'N latitudes and 78°59'E - 79°17'E longitudes (Verma and Ghosh, 2018). The glacier has experienced a rapid rate of retreat and it has been mapped by Geological Survey of India (GSI) since 1891 (Singh et al., 2017). The point in green color shown in Fig. 1(b) is NIH Laboratory to study meteorological parameters around glacier. The polygon shown in pink color represents glacier boundary and square box shown in black color represents CRU half degree grid box covering Gangotri glacier.

3. Data used

The widely accepted CRU dataset includes six climatic variables (mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapour pressure and cloud cover) and 2 secondary variables (frost day frequency and potential evapotranspiration) estimated from primary variables at 0.5° x 0.5° spatial resolution from 1901 to 2015 (Harris et al., 2014).

For this study, gridded time series dataset CRU TS v.400 released on 13th March 2017 available from 1901 to 2015 was used (Table 1). The available CRU dataset covers global land surface with a very fine spatial resolution of 0.5°x 0.5° latitude and longitude grid cells (Harris et al., 2014). Station Anomalies were interpolated into grids to obtain absolute monthly values of climate variables. The CRU TS v.400 dataset provides mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}) for 1901-2015.

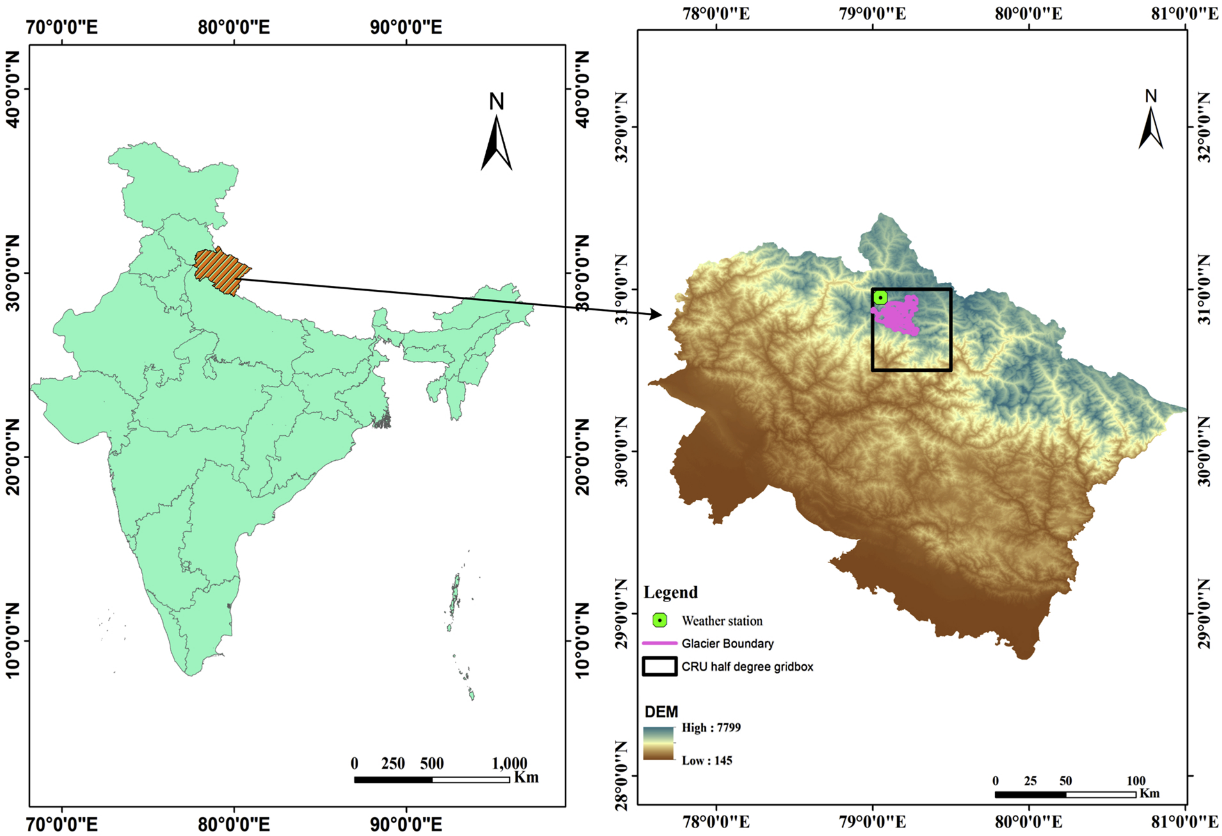
The observed temperature dataset has been acquired by NIH Roorkee from 2005 to 2015 on a daily basis for melting season of the glacier i.e. months of May, June, July, August and September. The hydro meteorological observatory of NIH is around 4 Km downstream from snout of Gangotri glacier as shown in Fig. 1(b).

4. Methodology

The 0.5° gridded CRU data was downloaded (available in netcdf format) and converted into raster format for extraction of information under ArcGIS environment. Further, CRU's (T_{max}, T_{min} and T_{mean}) time series data was masked for Gangotri glacier for grid centered at 30.75 N and 79.25 E. The methodology that has been followed in this study has been presented in the form of flowchart in Fig. 2.

4.1. Standardized anomalies

Standardized anomaly (z) is essential for comparing two datasets and is given by dividing anomaly by its corresponding standard deviation (S_x) (Piyoosh and Ghosh, 2016). Standard anomaly helps in removing influence of location in dataset and spread of data. It



(a) (b)

Fig. 1. Study Area (a) Map of India (b) DEM of Uttarakhand and location of NIH Laboratory, CRU gridbox and Gangotri glacier.

Table 1
Details of CRU dataset.

Sl. No.	Attributes	CRU
1	Data source	Climatic Research Unit, University of East Anglia, U.K.
2	Climatic variables (on monthly scales)	Mean Temp. (T_{mean}) Max. Temp. (T_{max}) Min. Temp. (T_{min})
3	Temporal Resolution	Monthly
4	Gridded Resolution	0.5 degree x 0.5 degree
5	Geographical Coverage	Global (Land only)
6	Period of record	1901-2015

is given by:

$$z = \frac{x_i - \bar{x}}{S_x} \tag{1}$$

Here, $x_i - \bar{x}$ is called as anomaly, which is difference between data value from its mean; x^{-} is mean of time series data; x_i is data value.

4.2. Correlation analysis

Correlation analysis is necessary to assess association between two datasets i.e. NIH and CRU temperature time series. The Pearson correlation coefficient (r_ρ), coefficient of determination (R^2) and statistical significance (*p values*) are used as various parameter to observe degree of closeness between two available datasets. The value of r_ρ varies between -1 to +1 where negative value indicates negative correlation and positive value indicates positive correlation between two variables.

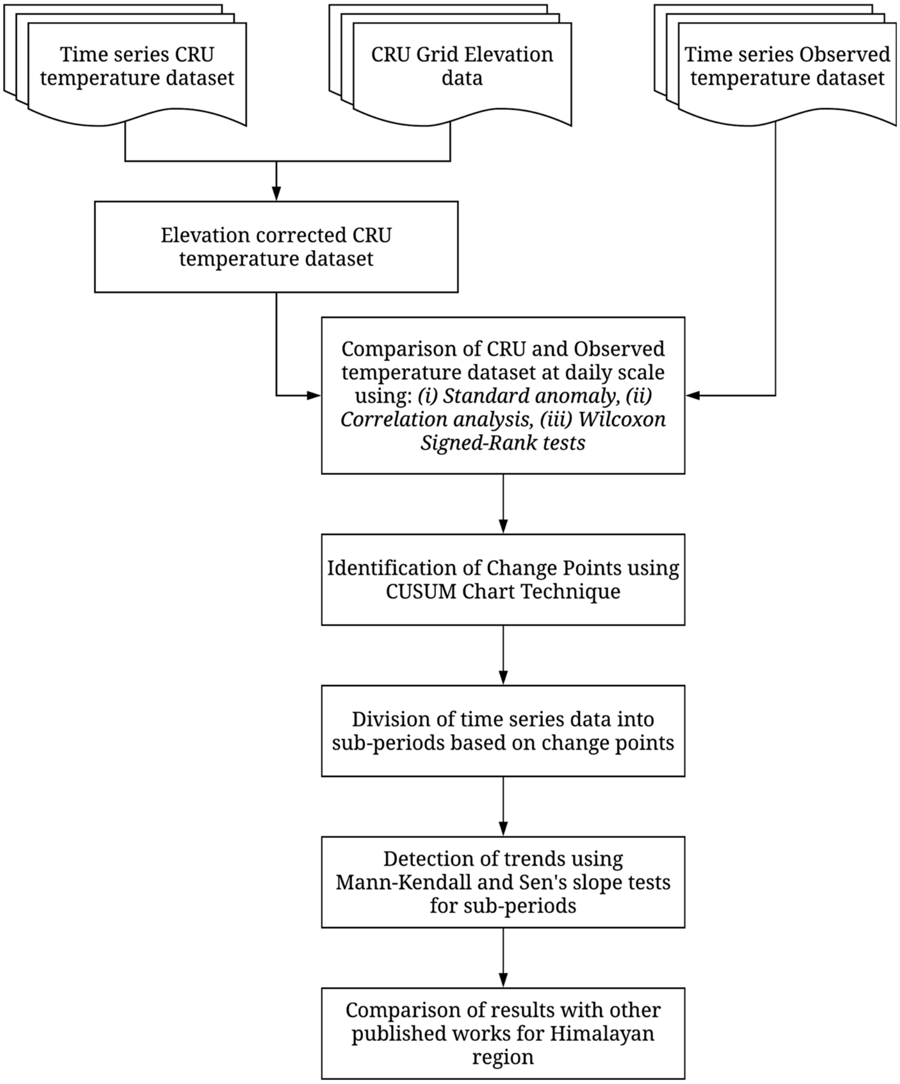


Fig. 2. Flowchart of methodology followed.

The Pearson correlation coefficient is defined as shown below:

$$r_\rho = \frac{[N\sum xy - (\sum x)(\sum y)]}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2]}} \tag{2}$$

where N = number of pairs of scores; $\sum x$ = sum of x scores; $\sum y$ = sum of y scores; $\sum x^2$ = sum of squared x scores; $\sum y^2$ = sum of squared y scores; $\sum xy$ = sum of product of paired scores.

The statistical significance of any test is determined with help of p values associated with each dataset. Here in this study, the statistical significance level of 5% is considered for correlation analysis. If value of p is less than 0.05, then correlation is significant and if p is greater than 0.05, then correlation is not significant. The coefficient of determination (R^2) is an important parameter in determination of closeness of data to fitted regression line. The value of R^2 varies between 0 and 1 where a value of 1 indicates that regression line perfectly fits the data and value of 0 indicates regression line explains none of the variability of response data around its mean.

4.3. Wilcoxon Signed-Rank (WSR) test

The WSR test is a non-parametric test used to compare two paired samples. The principle of this test is based on simple comparison of two samples. The number of cases is counted when first sample is greater than second sample along with size of difference within pairs and vice versa. It is important to notice sign of differences between two pairs in this test. The WSR test has been performed at 5% significance level.

The WSR test includes assumption of null hypothesis (H_o) which states that two samples follow same distribution while alternative hypothesis (H_a) states that distributions of two samples are different. If computed p value is greater than significance level of 0.05, then null hypothesis cannot be rejected and if p value is less than 0.05, then null hypothesis is rejected and alternative hypothesis is accepted. If null hypothesis is accepted then both samples are equivalent to each other and will yield same results while if alternative hypothesis is accepted then both samples are not equivalent to each other and will not yield same results.

4.4. Cumulative sum charts (CUSUM) and bootstrapping for change point detection

A change point analysis is a powerful tool for detection of a change that has occurred in a time series dataset over a long period of time. This technique is very helpful in understanding variation of climate that may have occurred in a region over a period of time. CUSUM Chart analysis is one such technique to study change point analysis. Page (1961) first studied and developed statistical procedure known as CUSUM chart technique to detect sequential changes in a time series data. Here, monthly gridded CRU data was statistically processed and converted into annual and seasonal mean values for further analysis. Further, CUSUM technique was applied to annual mean values of different temperature time series data to detect any change that has taken place. The combination of CUSUM and bootstrapping process were carried out to detect changes as discussed by Taylor (2000).

It should be noted that cumulative sums are not cumulative sums of values, instead, these are cumulative sums of differences between data points and their average (Taylor, 2000). In addition, these differences sum to zero and hence cumulative sum always ends at zero. The bootstrapping analysis is performed for determination of confidence interval for change which has occurred. Typically, 90% or 95% confidence level is required for a significant change to be detected. Here, time series data has been splitted into 2 sub series, *1 to m* and *m + 1 to n*. The average of each sub series is calculated and examined how well data fits two estimated averages. The point m for which minimum value of MSE is achieved, is considered as best estimator of last point before the change occurred and $m + 1$ denotes first point after the change occurred. Similarly, this process is repeated for each sub series to detect Level 2 change points that further divides subseries. The non-significant points are eliminated through backward elimination procedure. This process helps in finding significant change points at subsequent levels with confidence level associated with each change. This process helps in detection of multiple change points in a time series dataset.

4.5. Mann-Kendall (MK) and Sen's slope tests

The trend analysis of time series dataset consists of estimating magnitude of trend and its statistical significance (Jain and Kumar, 2012). The procedure for detection of trend and estimation of its magnitude was carried out in this study as discussed by Salmi (2002). The non-parametric statistical methods MK and Sen's slope were used to detect trend and magnitude of trend respectively.

The process consists of two phases, first is to detect presence of a monotonic decreasing or increasing trend and second is to find strength of trend by estimating slope of an existing trend. The objective of MK test is to test null hypothesis of no trend (H_o) i.e. data points are randomly ordered in time against alternative hypothesis (H_1) where data points show monotonic increasing or decreasing trend.

In MK test, if data points in any time series are less than 10 then S test is applied while for time series with data points more than 10 normal approximation is applied. This study consists of 115 data points on an annual scale, hence normal approximation statistics is used. The statistic Z has a normal distribution and a positive value of Z indicates an upward trend and negative value indicates a downward trend. This study includes four significance levels (α) at 0.001, 0.01, 0.05 and 0.1 carried out by two-tailed test. If the estimated value of $|Z| > Z_{\alpha/2}$, the null hypothesis is rejected with α level of significance.

Sen's slope non parametric test is used to find true slope of an existing trend. If data series contain n data values then there are $N = \frac{n*(n-1)}{2}$ values of slope estimates (Q_i). These N values are arranged in ascending order and Sen's estimator is given by median of these values. This can be decided as follows:

$$Q = Q_{(N+1)/2} \text{ if N is odd}$$

or

$$Q = \sqrt{[Q_{N/2} + Q_{(N+2)/2}]} \text{ if N is even}$$

Here, a positive value of Q indicates an increasing trend and a negative value indicates decreasing trend in a time series data.

5. Results

Results obtained from monthly gridded CRU and NIH dataset along with temperature variability from both datasets have been discussed below. The available monthly values of T_{max}, T_{min} and T_{mean} from CRU dataset was used to obtain annual and seasonal time series data. The maximum value in a time series dataset (T_{max}, T_{min} and T_{mean}) has been reported for months of July and August while minimum value has been reported for May. Generally, month of May marks the start of ablation season and September marks end of ablation season for Himalayan glaciers. The comparison of T_{max}, T_{min} and T_{mean} of CRU and NIH dataset is done based on standardized anomaly curves, Correlation and WSR tests only for melting season from 2005 to 2015.

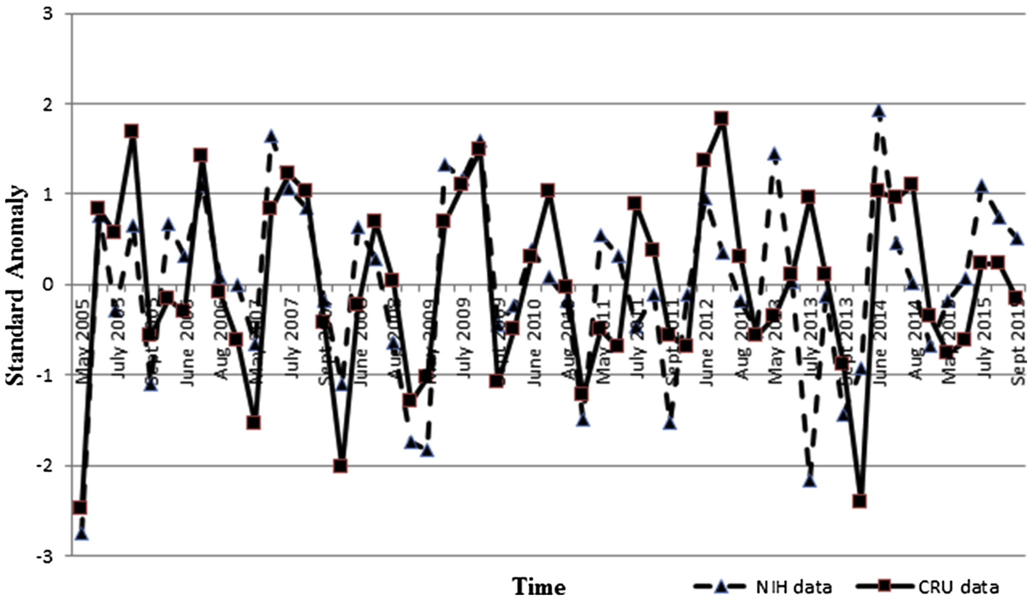


Fig. 3. Standard anomaly for T_{max} of CRU vs NIH dataset.

5.1. Standard anomaly

Monthly temperature values of CRU and NIH datasets has been compared with the help of standardized anomaly as shown in Figs. 3–5. The comparison of both dataset is done for common time period of 2005–2015 for months from May to September. The graphical pattern shown by standard anomalies of both datasets for T_{max}, T_{min} and T_{mean} indicates similarity in pattern for defined time period as evident from Figs. 3–5 respectively.

However, difference between standard anomaly values for both datasets is more for T_{max} in comparison to T_{mean} and T_{min}. The standard anomaly pattern for T_{max} in Fig. 3 shows variations at few time periods with large variations occurring at July and August (2005), May and September (2006), May (2008), May and June (2011), July (2012), May and July (2013), May and June (2014). The bias in monthly values for both datasets have been shown in Tables 2–4 for T_{max}, T_{min} and T_{mean} respectively.

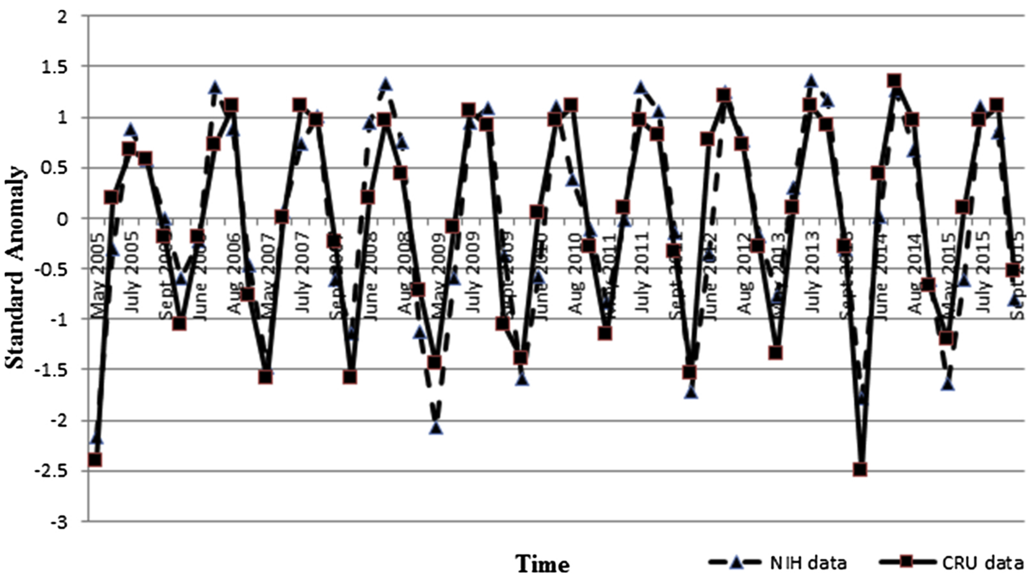


Fig. 4. Standard anomaly for T_{min} of CRU vs NIH dataset.

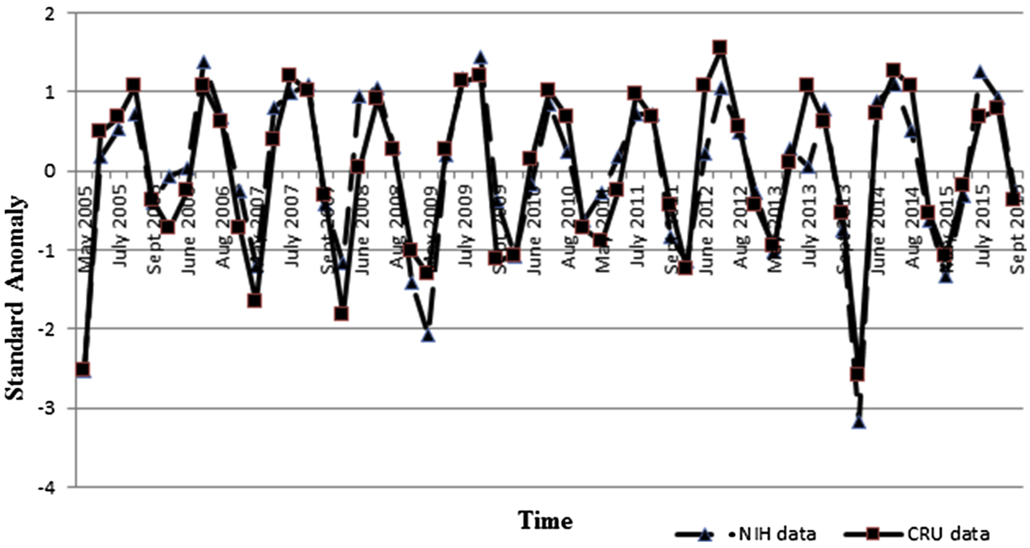


Fig. 5. Standard anomaly for T_{mean} of CRU vs NIH dataset.

Table 2
Monthly bias values in NIH and CRU datasets for T_{max} time series.

Years	Source	May	June	July	August	September
2005	NIH	−2.74	0.76	−0.30	0.66	−1.11
	CRU	−2.48	0.82	0.56	1.68	−0.56
2006	NIH	0.67	0.32	1.09	0.08	−0.01
	CRU	−0.17	−0.3	1.42	−0.1	−0.63
2007	NIH	−0.67	1.65	1.07	0.85	−0.18
	CRU	−1.55	0.82	1.22	1.02	−0.43
2008	NIH	−1.11	0.64	0.28	−0.64	−1.73
	CRU	−2.02	−0.23	0.69	0.03	−1.29
2009	NIH	−1.82	1.32	1.17	1.59	−0.44
	CRU	−1.03	0.69	1.09	1.49	−1.09
2010	NIH	−0.23	0.38	0.09	−0.18	−1.49
	CRU	−0.50	0.30	1.02	−0.03	−1.22
2011	NIH	0.54	0.32	−0.47	−0.12	−1.53
	CRU	−0.50	−0.70	0.89	0.36	−0.56
2012	NIH	−0.11	0.95	0.35	−0.18	−0.51
	CRU	−0.70	1.35	1.82	0.30	−0.56
2013	NIH	1.44	0.03	−2.18	−0.13	−1.44
	CRU	−0.37	0.10	0.96	0.10	−0.89
2014	NIH	−0.92	1.93	0.46	0.01	−0.68
	CRU	−2.41	1.02	0.96	1.09	−0.37
2015	NIH	−0.18	0.07	1.10	0.73	0.52
	CRU	−0.76	−0.63	0.23	0.23	−0.17

5.2. Correlation analysis and R^2 results

The Pearson correlation coefficient (r_ρ) and R^2 along with p values for each coefficient have been estimated for available temperature data from NIH and CRU for assessment of quality of CRU dataset. Since NIH data is available only for months May to September from 2005 to 2015, therefore correlation analysis of CRU data with NIH data has been done only for common time period. The standard anomaly obtained from both datasets has been used for correlation analysis. Table 5 shows values of r_ρ for T_{max}, T_{min} and T_{mean} on monthly and yearly scale. The monthly scale includes estimation of r_ρ from 2005 to 2015 and yearly scale includes estimation of r_ρ from May to September for each year respectively. The simple regression analysis has been performed with estimation of R^2 values and its graphical representation has been shown in Fig. 6.

For T_{mean}, r_ρ is positive for monthly average with 0.15 and 0.86 as the minimum and maximum value respectively while 0.81 and 1.0 as the minimum and maximum value on yearly scale respectively. The overall average r_ρ between NIH and CRU data for T_{mean} comes out to be 0.92. The graphical representation with regression and correlation analysis for T_{mean} on yearly basis has been shown in Fig. 7(a).

Table 3
Monthly bias values in NIH and CRU datasets for T_{min} time series.

Years	Source	May	June	July	August	September
2005	NIH	−2.17	−0.31	0.89	0.58	0.01
	CRU	−2.40	0.20	0.68	0.58	−0.19
2006	NIH	−0.60	−0.22	1.29	0.89	−0.47
	CRU	−1.05	−0.19	0.73	1.11	−0.76
2007	NIH	−1.47	0.07	0.74	1.01	−0.61
	CRU	−1.58	0.01	1.11	0.97	−0.24
2008	NIH	−1.15	0.94	1.32	0.76	−1.12
	CRU	−1.58	0.20	0.97	0.44	−0.72
2009	NIH	−2.07	−0.60	0.94	1.09	−0.37
	CRU	−1.44	−0.09	1.06	0.92	−1.05
2010	NIH	−1.58	−0.57	1.11	0.39	−0.11
	CRU	−1.39	0.05	0.97	1.11	−0.28
2011	NIH	−0.84	−0.02	1.30	1.06	−0.14
	CRU	−1.15	0.10	0.97	0.82	−0.33
2012	NIH	−1.72	−0.35	1.25	0.76	−0.18
	CRU	−1.53	0.78	1.21	0.73	−0.28
2013	NIH	−0.76	0.31	1.37	1.17	−0.30
	CRU	−1.34	0.10	1.11	0.92	−0.28
2014	NIH	−1.79	0.01	1.27	0.68	−0.60
	CRU	−2.50	0.44	1.35	0.97	−0.67
2015	NIH	−1.63	−0.61	1.10	0.85	−0.80
	CRU	−1.20	0.10	0.97	1.11	−0.52

Table 4
Monthly bias values in NIH and CRU datasets for T_{mean} time series.

Year	Source	May	June	July	August	September
2005	NIH	−2.53	0.17	0.53	0.72	−0.40
	CRU	−2.52	0.50	0.67	1.08	−0.38
2006	NIH	−0.06	0.04	1.38	0.68	−0.25
	CRU	−0.72	−0.26	1.08	0.61	−0.72
2007	NIH	−1.20	0.79	1.00	1.09	−0.42
	CRU	−1.65	0.38	1.19	1.02	−0.32
2008	NIH	−1.17	0.95	1.06	0.30	−1.41
	CRU	−1.83	0.03	0.90	0.26	−1.01
2009	NIH	−2.08	0.21	1.18	1.45	−0.37
	CRU	−1.30	0.26	1.13	1.19	−1.13
2010	NIH	−1.09	−0.16	0.83	0.24	−0.64
	CRU	−1.07	0.15	1.02	0.67	−0.72
2011	NIH	−0.27	0.18	0.72	0.72	−0.84
	CRU	−0.90	−0.26	0.96	0.67	−0.43
2012	NIH	−1.14	0.22	1.04	0.49	−0.28
	CRU	−1.25	1.08	1.54	0.55	−0.43
2013	NIH	−1.01	0.28	0.06	0.79	−0.74
	CRU	−0.96	0.09	1.08	0.61	−0.55
2014	NIH	−3.18	0.87	1.10	0.51	−0.63
	CRU	−2.58	0.73	1.25	1.08	−0.55
2015	NIH	−1.33	−0.32	1.25	0.93	−0.26
	CRU	−1.07	−0.20	0.67	0.79	−0.38

Similarly for T_{max}, r_ρ is positive for all months varying from 0.11 to 0.78 as the minimum and maximum value respectively. However, r_ρ is negative for 2011 and 2013 on yearly scale and positive for rest of the years while the overall average for all years is estimated to be 0.64. The graphical representation of correlation analysis for T_{max} on yearly scale has been shown in Fig. 7(b) where positive correlation is represented by red line and negative correlation is represented by blue line respectively.

For T_{min}, r_ρ is always positive for all months and years of the defined time period. However, r_ρ value ranges from 0.08 to 0.63 on monthly scale and 0.90 to 0.98 on yearly basis. The overall average of r_ρ for T_{min} is 0.92 with graphical representation as shown in Fig. 7(c).

5.3. WSR test

The results of WSR test has been performed using standard anomaly of both datasets and has been shown in Table 6. The result indicates that both samples are equivalent to each other and accept null hypothesis (H_o) with p values greater than 0.05 and will yield same results for T_{max}, T_{min} and T_{mean} on yearly scale. The results show equivalence of both datasets with p values greater than 0.05 for

Table 5
Correlation coefficient (r_ρ) values for NIH and CRU data.

2005 - 2015				2005 - 2015			
	T_{mean}	T_{max}	T_{min}		T_{mean}	T_{max}	T_{min}
Months	r_ρ	r_ρ	r_ρ	**Years**	r_ρ	r_ρ	r_ρ
May	**0.86**	**0.78**	**0.63**	2005	**1**	**0.97**	**0.97**
June	0.35	**0.74**	0.08	2006	**0.97**	0.86	**0.93**
July	0.15	0.11	0.17	2007	**0.97**	**0.91**	**0.98**
Aug	**0.66**	**0.71**	0.08	2008	**0.9**	0.72	**0.94**
Sept	0.38	**0.66**	0.48	2009	**0.92**	**0.92**	**0.91**
				2010	**0.98**	0.84	**0.92**
				2011	0.83	−0.1	**0.98**
				2012	**0.95**	0.8	**0.9**
				2013	0.81	−0.36	**0.98**
				2014	**0.99**	0.71	**0.98**
				2015	**0.98**	**0.96**	**0.97**
				overall	**0.92**	**0.64**	**0.92**

Note: Values of r_ρ in bold are significant at 5% significance level.

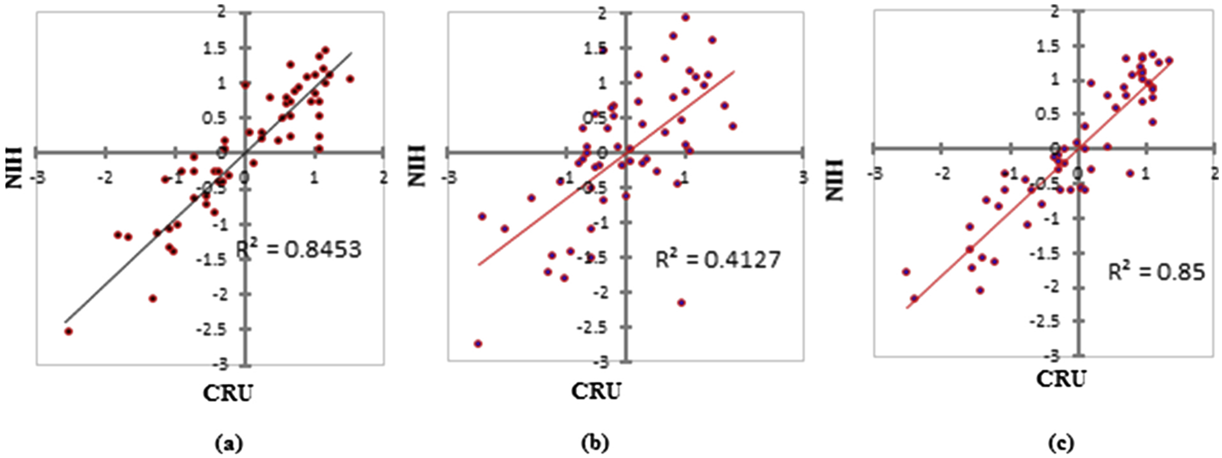


Fig. 6. Correlation results for 2005–2015 (a) T_{mean} (b) T_{max} (c) T_{min}.

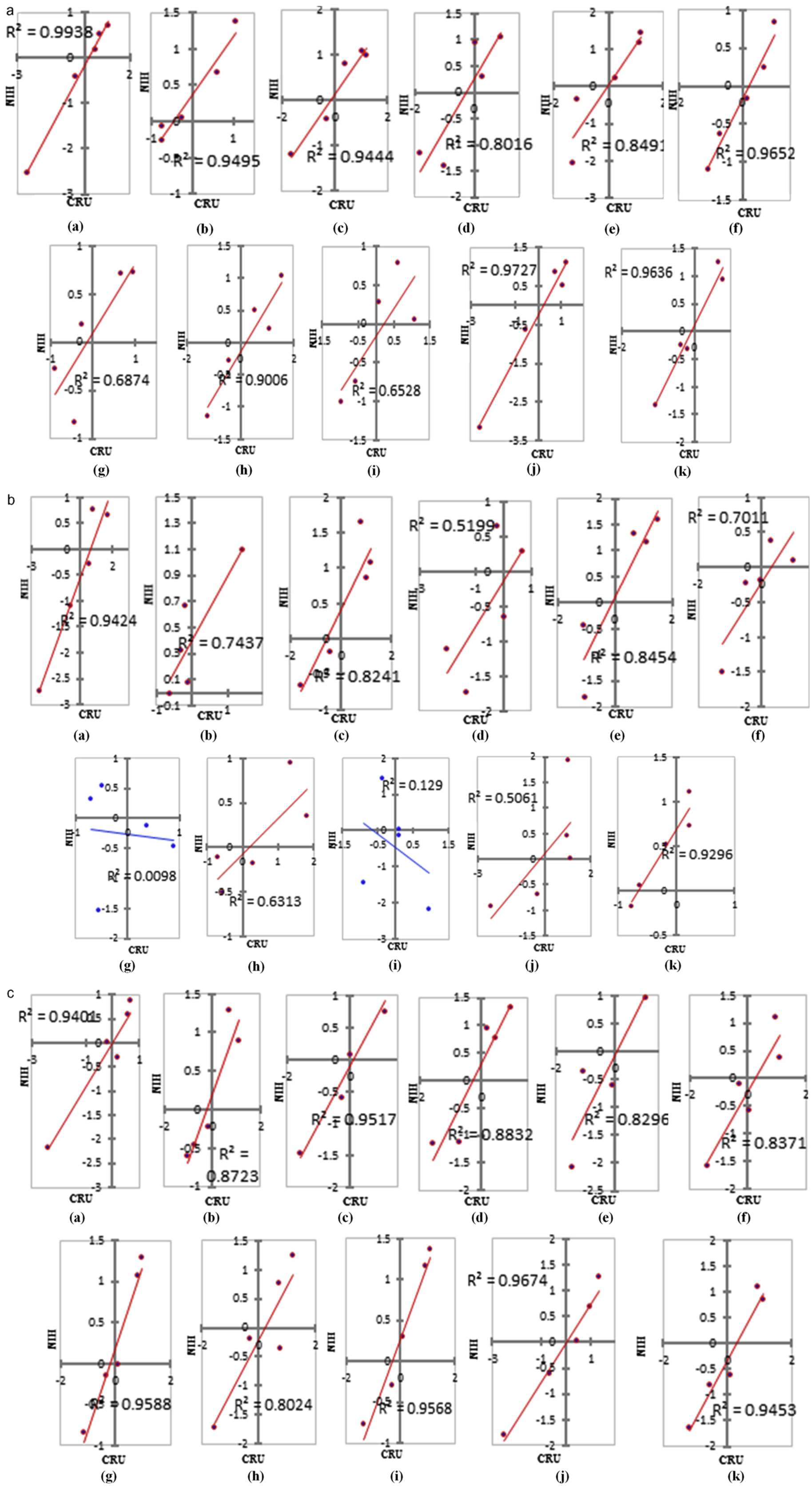
T_{mean} and T_{min} on monthly scale as well but non-equivalence of samples has been estimated for May, June and July for T_{max} temperature time series with p values being lower than 0.05 and accept the alternative hypothesis (H_a).

5.4. Change point analysis

Once it has been established that standard anomaly of CRU data is in high correlation with NIH data then CRU data has been utilized from 1901 to 2015 to study temperature trend over Gangotri glacier. CUSUM chart technique has been used to find change points in temperature data of CRU. The results of identification of change points in annual mean values of T_{mean}, T_{max} and T_{min} for CRU dataset has been presented in Fig. 8. The interannual variability in different time series data can be studied from plots of CUSUM values as shown in Fig. 9. The change in background color from blue to yellow or vice versa in Fig. 8 represents the identified change points for respective time series and red line represents maximum range of temperature fluctuation under no change in trend (Fig. 8).

The change point for annual T_{mean} was identified at 1974 with 98% confidence interval and at 1999 with 100% confidence interval as shown in Table 7. Prior to 1974, the annual T_{mean} was 3.77 °C and after 1974 T_{mean} was changed to 3.61 °C. Similarly, before 1999 T_{mean} estimated was 3.61 °C and after 1999 T_{mean} is shifted to 4.47 °C. It should be noted that less is the confidence interval range more accurate is the change point estimation. The level associated with each change point indicates the importance of the change. Here, level 1 means change detected in first pass while level 2 means change detected on second pass through the data. The number of level depends on the number of change points identified in time series data. Tables 8 and 9 represents change points identified through cusum technique for T_{max} and T_{min} of CRU data. There were 3 change points identified for T_{max} and T_{min} respectively. The change points for T_{max} were identified at 1941, 1975 and 1999 with 100% confidence interval.

The year 1999 can be said as most accurately identified change point as confidence interval range associated with this change point is smallest. Similarly, identified change points for T_{min} are 1941, 1965 and 1999 with 100%, 100% and 94% confidence interval respectively.



(caption on next page)

Fig. 7. a) Correlation results for standard anomaly of T_{mean}. b) Correlation results for standard anomaly of T_{max}. c) Correlation results for standard anomaly of T_{min}.

Table 6
Wilcoxon Signed–Rank test results for standard anomaly of CRU and NIH data.

	2005 - 2015					
	T_{mean}		T_{max}		T_{min}	
Months	WSR	p value	WSR	p value	WSR	p value
May	**EQ**	0.77	NEQ	0.01	**EQ**	0.32
June	**EQ**	0.58	NEQ	0.02	**EQ**	0.15
July	**EQ**	0.41	NEQ	0.02	**EQ**	0.12
Aug	**EQ**	0.97	**EQ**	0.08	**EQ**	0.97
Sept	**EQ**	0.90	**EQ**	0.83	**EQ**	0.64

2005 - 2015						
	T_{mean}		T_{max}		T_{min}	
Years	WSR	p value	WSR	p value	WSR	p value
2005	**EQ**	0.06	**EQ**	0.06	**EQ**	0.81
2006	**EQ**	0.06	**EQ**	0.19	**EQ**	0.31
2007	**EQ**	0.63	**EQ**	0.31	**EQ**	0.81
2008	**EQ**	0.31	**EQ**	0.81	**EQ**	0.31
2009	**EQ**	1	**EQ**	0.63	**EQ**	1
2010	**EQ**	0.19	**EQ**	0.63	**EQ**	0.31
2011	**EQ**	0.62	**EQ**	1	**EQ**	0.13
2012	**EQ**	0.63	**EQ**	0.63	**EQ**	0.81
2013	**EQ**	0.62	**EQ**	0.44	**EQ**	0.13
2014	**EQ**	0.19	**EQ**	1	**EQ**	0.81
2015	**EQ**	0.81	**EQ**	0.06	**EQ**	0.13
overall	**EQ**	1	**EQ**	0.74	**EQ**	0.77

Note: EQ stands for Equivalence of standard anomaly of CRU and NIH data at 5% significance level; NEQ stands for Non Equivalence of standard anomaly of both datasets at 5% significance level.

5.5. Mann-Kendall and Sen's slope estimation tests

The non-parametric MK and Sen's slope tests were carried out on annual, seasonal and monthly scale on available time series data. The positive value of Z indicates an increasing trend for T_{mean}, T_{max} and T_{min} on an annual scale. The annual T_{mean}, T_{max} and T_{min} shows statistically significant increasing trend with a slope of about 0.006 °C/year, 0.001 °C/year and 0.01 °C/year respectively as shown in Table 10. However, increasing trend shown by T_{mean} and T_{min} is significant with 99.9% confidence level while increasing trend shown by T_{max} is not significant.

The MK and Sen's slope results on seasonal scale for T_{mean}, T_{max} and T_{min} has been shown below in Table 11. The seasonal T_{mean} shows statistically significant trends for Pre-monsoon, Post-monsoon and Winter seasons with an increasing trend of about 0.006 °C/year with 95% confidence level, 0.01 °C/year and 0.009 °C/year with 99.9% confidence level respectively. There is no significant trend shown by T_{mean} for monsoon season.

For T_{max}, there is significant decreasing trend of about 0.006 °C/year with 99.9% confidence level for monsoon season. The other seasons show an increasing trend for T_{max} with winter season being the only significant one with 99% confidence level indicating more warming winters. Here for T_{min}, all seasons shows statistically significant increasing trend for pre-monsoon, monsoon, post-monsoon and winter by about 0.009 °C/year, 0.007 °C/year, 0.015 °C/year and 0.013 °C/year respectively.

The non-parametric tests were used for detection of trend on time series temperature data on monthly scale. T_{min} shows significant increasing trend for all months in a year except May indicating warming trend over study area with temperature rate ranging from 0.005 °C/year for month of July and August to 0.018 °C/year for February and December as shown in Table 12. T_{max} show significant decreasing trend for months of June, July, August and September with a rate of 0.01 °C/year, 0.006 °C/year,0.005 °C/year and 0.003 °C/year with an increasing trend for months of February, November and December with 0.011 °C/year, 0.008 °C/year and 0.008 °C/year respectively. The results for T_{mean} show an increasing trend for months of February, March, April, September, October, November and December with rates of about 0.014 °C/year, 0.009 °C/year, 0.006 °C/year, 0.003 °C/year, 0.005 °C/year, 0.014 °C/year and 0.013 °C/year respectively.

6. Discussion

The standard anomaly, WSR test and correlation tests were used as a parameter to assess quality of CRU data with respect to observed NIH data. It was important to compare both datasets for common time period in order to observe order of agreement between them. The correlation results at monthly scale exhibit generally low r_ρ and R^2 values while yearly scale exhibit high r_ρ and R^2 values. The WSR test prove to be very important tool to assess the equivalence of two datasets with both datasets being equivalent to each other on yearly and monthly scale for all 3 temperature time series except for 3 cases for T_{max} at monthly scale.

There are total of 8 change points identified in 3 time series data (1974 and 1999 for T_{mean}; 1941, 1975 and 1999 for T_{max}; 1941, 1965 and 1999 for T_{min}). CUSUM chart gives important results of variation in mean value of different time series after identified change points. For T_{mean}, mean value reduced by an amount of 0.16 °C at first identified change point of 1974. Similarly, mean value was found to be increased by an amount of 0.86 °C at 1999. CUSUM chart technique identified 3 change points for T_{max} (1941, 1975 and 1999) and T_{min} (1941, 1965 and 1999) each. For T_{max}, mean value was increased by 0.37 °C at 1941 with a reduction in mean value by 0.61 °C at 1975 and again an increase by an amount of 0.58 °C in 1999. For T_{min}, mean value was increased by an amount of

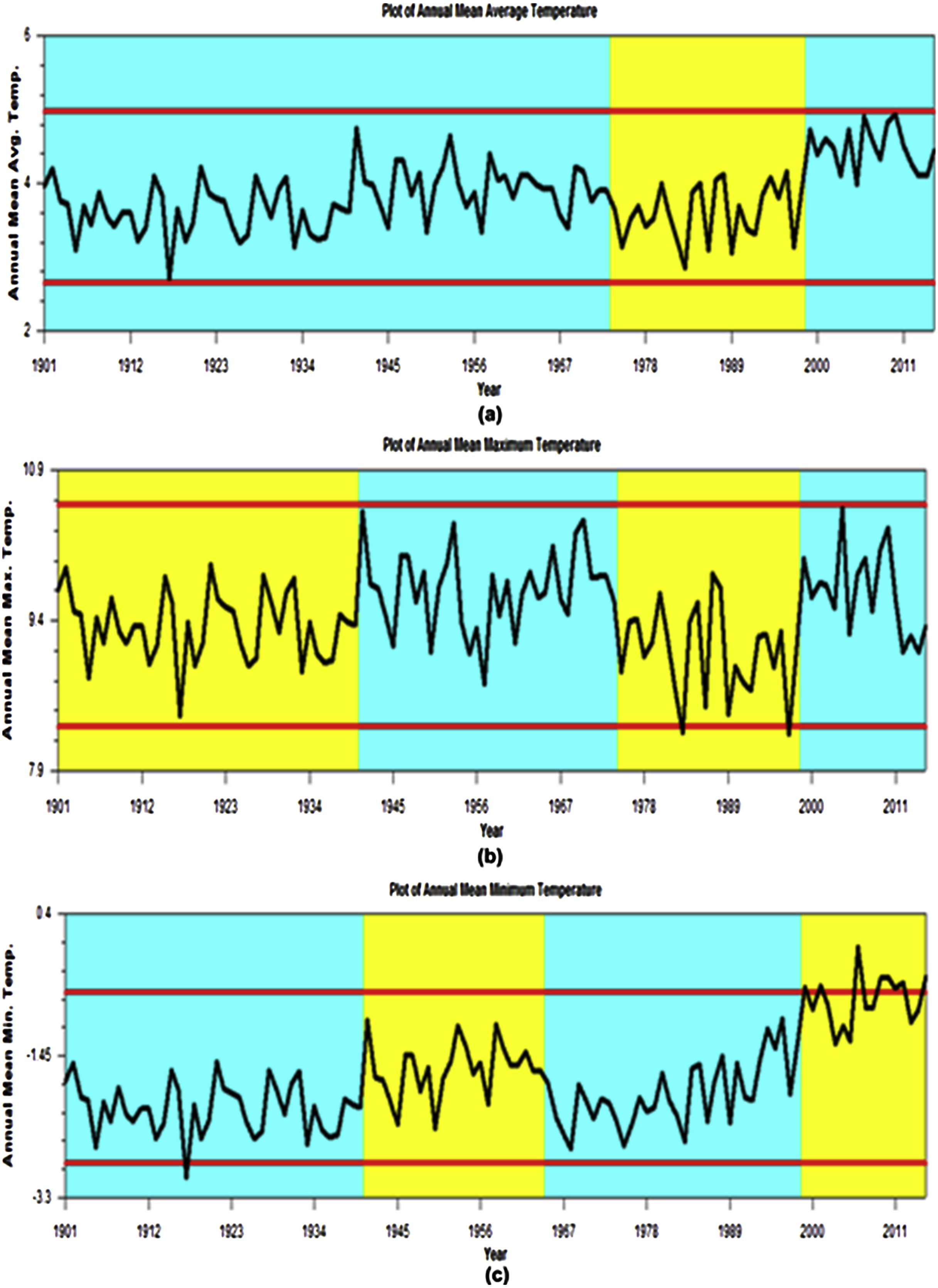


Fig. 8. Plot of CRU data (a) Annual mean T_{mean} (b) Annual mean T_{max} (c) Annual mean T_{min}.

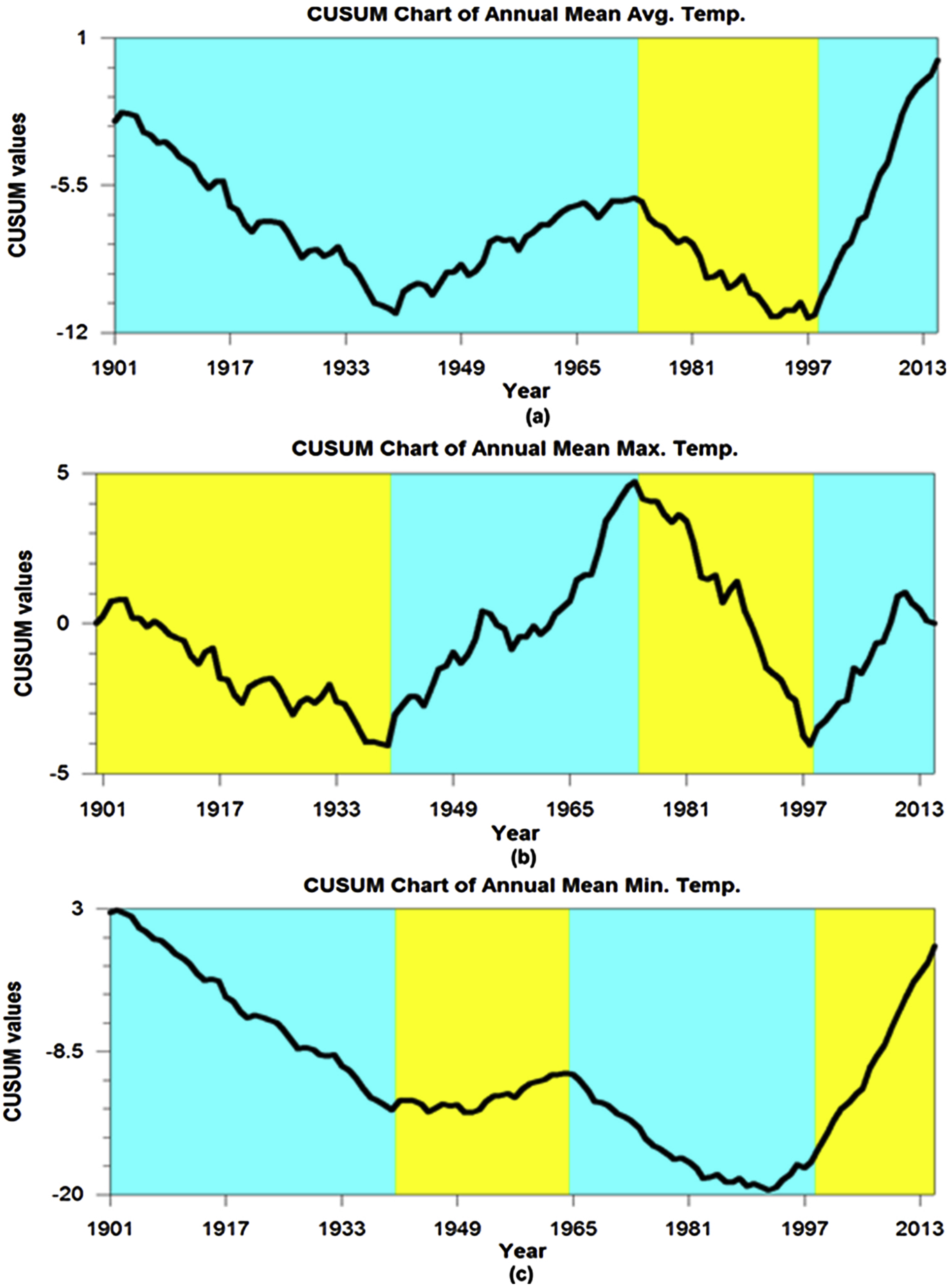


Fig. 9. Plot of CUSUM values (a) Annual mean T_{mean} (b) Annual mean T_{max} (c) Annual mean T_{min}.

Table 7
Details of detected change points for T_{mean} of CRU data.

Year	Confidence Interval	Confidence Level	From	To	Level
1974	(1903, 1997)	98%	3.77	3.61	4
1999	(1997, 2000)	100%	3.61	4.47	1

0.52 °C in 1941 with a decrease in mean value by 0.33 °C in 1965 and then a big increase by an amount of 1.23 °C in 1999.

The non-parametric MK and Sen's slope tests identified that T_{mean} and T_{min} showed significant increasing trend with a rate of about 0.006 °C/year and 0.01 °C/year respectively and T_{max} showed no significant trend on an annual scale. The non-parametric tests revealed significant results on seasonal scale where T_{mean}, T_{max} and T_{min} showed significant increasing trend for winter season with a

Table 8
Details of detected change points for T_{max} of CRU data.

Year	Confidence Interval	Confidence Level	From	To	Level
1941	(1933, 1955)	100%	9.34	9.71	4
1975	(1970, 1981)	100%	9.71	9.10	2
1999	(1993, 2003)	100%	9.10	9.68	1

Table 9
Details of detected change points for T_{min} of CRU data.

Year	Confidence Interval	Confidence Level	From	To	Level
1941	(1935, 1946)	100%	−2.14	−1.62	4
1965	(1955, 1985)	100%	−1.62	−1.95	1
1999	(1998, 1999)	94%	−1.95	−0.72	2

Table 10
Mann-Kendall and Sen's slope test for annual T_{mean}, T_{max} and T_{min} for Gangotri glacier.

Time	Z			S		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Annual	4.06	0.52	5.95	0.006***	0.001	0.010***

Note: ***, ** and * indicates the significance of trends with 99.9%, 99% and 95% confidence level respectively.

Table 11
Mann-Kendall and Sen's slope test for seasonal T_{mean}, T_{max} and T_{min} for Gangotri glacier.

Season	Z			S		
	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}
Pre-monsoon	2.12	0.86	3.16	0.006*	0.003	0.009**
Monsoon	0.24	−4.15	3.97	0.000	−0.006***	0.007***
Post-monsoon	4.55	1.63	5.35	0.010***	0.004	0.015***
Winter	4.53	2.58	5.83	0.009***	0.006**	0.013***

Note: ***, ** and * indicates the significance of trends with 99.9%, 99% and 95% confidence level respectively.

Table 12
Mann-Kendall and Sen's slope test for monthly T_{mean}, T_{max} and T_{min} for Gangotri glacier.

	T_{mean}		T_{max}		T_{min}	
	Z	S	Z	S	Z	S
Jan	1.27	0.004	−0.05	0	1.84	0.006+
Feb	3.65	0.014***	2.52	0.011*	4.53	0.018***
Mar	2.08	0.009*	1.35	0.007	2.48	0.01*
Apr	1.65	0.006+	0.82	0.003	2.44	0.01*
May	−0.03	0	−1.38	−0.005	1.6	0.006
Jun	−0.85	−0.002	−3.07	−0.01**	2.62	0.007**
July	−0.21	0	−2.61	−0.006**	2.6	0.005**
Aug	−0.11	0	−2.91	−0.005**	2.48	0.005*
Sept	1.78	0.003+	−1.77	−0.003+	4.66	0.01***
Oct	2.22	0.005*	−0.5	0	3.91	0.011***
Nov	5.14	0.014***	2.81	0.008**	6.17	0.02***
Dec	5.26	0.013***	2.88	0.008**	6.13	0.018***

Note: ***, **, * and + indicates the significance of trends with 99.9%, 99%, 95% and 90% confidence level respectively.

rate of about 0.009 °C/year, 0.006 °C/year and 0.013 °C/year respectively. The increasing trend for T_{min} with 95% and 99% confidence interval for all seasons indicates the more warming trend over the gridbox. The only decreasing trend is shown by T_{max} and it is 0.006 °C/year for monsoon season.

These non-parametric tests were also applied on monthly values of different time series CRU dataset. The monthly results show an evidence of significant warming of T_{min} for all months except May from 1901 to 2015. For T_{max}, significant decreasing trend is found

for months of June to September. The months of November and December show significant increasing trend for T_{max} indicating warmer winters along with significant increasing trend for month of February. For T_{mean}, significant warming trend were found for months of February, March, April, September, October, November and December with no significant trends for remaining months.

7. Conclusion

Different temperature time series data (T_{mean}, T_{max} and T_{min}) of CRU and NIH dataset were analyzed on monthly scale from May to September for a period of 11 years from 2005 to 2015. The standard anomaly curves, WSR test and correlation results describes closeness of CRU data to NIH dataset very well, therefore it was concluded that open source CRU data can be used to study temperature trend analysis for Gangotri glacier.

The non-parametric MK and Sen's slope tests provided various significant trend results at monthly, seasonal and annual scale for CRU data. The results obtained are in agreement with results reported by other studies (Bhutiyani et al., 2007; Shrestha et al., 1999) for different parts of Himalaya. The significant rising trend shown by T_{min} and absence of any significant trend for T_{max} reported in this study is in agreement with other study for Himalayas. The CUSUM technique identified change points with 1999 being common year in different time series data.

Overall, results indicate warming trend over CRU gridbox which will certainly have an impact on glacier melt. Therefore, an additional study based on precipitation trend analysis and its correlation with temperature trends will prove to be helpful in order to understand behavior of meteorological variables over the glacierised gridbox.

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